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A Brief Summary of The SUSY Les Houches Accord 2

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Abstract

The SUSY Les Houches Accord 2 (SLHA2) extends the conventions described in [1] to include the MSSM with flavour violation, R-parity violation, and/or CP violation, as well as to the MSSM with an extra gauge singlet chiral superfield. This report contains a brief summary of the agreements reached so far.

1 Introduction

The states and couplings appearing in the general minimal supersymmetric standard model (MSSM) can be defined in a number of ways. Indeed, it is often advantageous to use different choices for different applications and hence no unique set of conventions prevails at present. In principle, this is not a problem; translations between different conventions can usually be carried out without ambiguity. From the point of view of practical application, however, such translations are, at best, tedious, and at worst they introduce an unnecessary possibility for error.

To deal with this problem, and to create a more transparent situation for non-experts, the original SUSY Les Houches Accord (SLHA1) was proposed [1]. This accord uniquely defines a set of conventions for supersymmetric models together with a common interface between codes. However, SLHA1 was designed exclusively with the MSSM with real parameters and R-parity conservation in mind. Some recent public codes [2–10] are either implementing extensions to this base model or are anticipating such extensions. We therefore here present extensions of the SLHA1 relevant for R-parity violation (RPV), flavour violation, and CP-violation (CPV) in the minimal supersymmetric standard model (MSSM). We also consider next-to-minimal models which we shall collectively label by the acronym NMSSM. Since the SLHA2 agreements have not yet been published, this summary should be regarded as preliminary.

For simplicity, we still limit the scope of the SLHA2 in two regards: for the MSSM, we restrict our attention to *either* CPV or RPV, but not both. For the NMSSM, we define one catch-all model and extend the SLHA1 mixing only to include the new states, with CP, R-parity, and flavour still assumed conserved. For brevity, this report does not include a discussion of the super-MNS basis for lepton flavour violation

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The conventions described here are a superset of those of the original SLHA1, unless explicitly stated otherwise. We use ASCII text for input and output, all dimensionful parameters are taken to be in appropriate powers of GeV, and the output formats for SLHA2 data `BLOCK`s follow those of SLHA1. All angles are in radians. In a few cases it has been necessary to replace the original conventions. This is clearly remarked upon in all places where it occurs, and the SLHA2 conventions then supersede the SLHA1 ones.

2 The SLHA2 Conventions

2.1 Flavour Violation

The CKM basis is defined to be the one in which the quark mass matrix is diagonal. In the super-CKM basis [11] the squarks are rotated by exactly the same amount as their respective quark superpartners, regardless of whether this makes the squark mass matrices diagonal or not. Misalignment between the quark and squark sectors thus results in flavour off-diagonal terms remaining in the squark sector.

In this basis, the 6×6 squark mass matrices are defined as

$$\mathcal{L}_{\tilde{q}}^{\rm mass} \;=\; -\,\Phi_u^\dagger\,\mathcal{M}_{\tilde{u}}^2\,\Phi_u - \Phi_d^\dagger\,\mathcal{M}_{\tilde{d}}^2\,\Phi_d\;, \tag{1}$$

where $\Phi_u = (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)^T$ and $\Phi_d = (\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R)^T$. We diagonalise the squark mass matrices via 6×6 unitary matrices $R_{u,d}$, such that $R_{u,d}\,\mathcal{M}^2_{\tilde{u},\tilde{d}}\,R^\dagger_{u,d}$ are diagonal matrices with increasing mass squared values. We re-define the existing PDG codes for squarks to enumerate the mass eigenstates in ascending order:
$(\tilde{d}_1, \tilde{d}_2, \tilde{d}_3, \tilde{d}_4, \tilde{d}_5, \tilde{d}_6)$ = `(1000001, 1000003, 1000005, 2000001, 2000003, 2000005)`,
$(\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4, \tilde{u}_5, \tilde{u}_6)$ = `(1000002, 1000004, 1000006, 2000002, 2000004, 2000006)`.

The flavour violating parameters of the model are specified in terms of the CKM matrix together with five 3×3 matrices of soft SUSY-breaking parameters given in the super-CKM basis

$$\hat{m}^2_{\tilde{Q}}\;,\quad \hat{m}^2_{\tilde{u}}\;,\quad \hat{m}^2_{\tilde{d}}\;,\quad \hat{T}_U\;,\quad \hat{T}_D\;. \tag{2}$$

Analogous rotations and definitions are used for the lepton flavour violating parameters, in this case using the super-MNS basis. This will be further elaborated on in the journal version of this report. Below, we refer to the combined basis as the super-CKM/MNS basis.

2.2 R-parity Violation

We write the R-parity violating superpotential as

$$\begin{aligned} W_{\rm RPV} \;=\; & \epsilon_{ab}\left[\frac{1}{2}\lambda_{ijk}L_i^a L_j^b \bar{E}_k + \lambda'_{ijk}L_i^a Q_j^{bx}\bar{D}_{kx} - \kappa_i L_i^a H_2^b\right] \\ & + \frac{1}{2}\lambda''_{ijk}\epsilon^{xyz}\bar{U}_{ix}\bar{D}_{jy}\bar{D}_{kz}, \end{aligned} \tag{3}$$

where $x, y, z = 1, \ldots, 3$ are fundamental $\mathrm{SU}(3)_C$ indices and ϵ^{xyz} is the totally antisymmetric tensor in 3 dimensions with $\epsilon^{123} = +1$. In eq. (3), $\lambda_{ijk}, \lambda'_{ijk}$ and κ_i break lepton number, whereas λ''_{ijk} violate baryon number.

The trilinear R-parity violating terms in the soft SUSY-breaking potential are

$$\begin{aligned} V_{3,\mathrm{RPV}} &= \epsilon_{ab}\left[\frac{1}{2}(T)_{ijk}\tilde{L}^a_{iL}\tilde{L}^b_{jL}\tilde{e}^*_{kR} + (T')_{ijk}\tilde{L}^a_{iL}\tilde{Q}^b_{jL}\tilde{d}^*_{kR}\right] \\ &\quad + \frac{1}{2}(T'')_{ijk}\epsilon_{xyz}\tilde{u}^{x*}_{iR}\tilde{d}^{y*}_{jR}\tilde{d}^{z*}_{kR} + \mathrm{h.c.} \quad . \end{aligned} \tag{4}$$

Note that we do not factor out the λ couplings (e.g. as in $T_{ijk}/\lambda_{ijk} \equiv A_{\lambda,ijk}$).

The bilinear R-parity violating soft terms (all lepton number violating) are

$$V_{2,\mathrm{RPV}} = -\epsilon_{ab}D_i\tilde{L}^a_{iL}H^b_2 + \tilde{L}^\dagger_{iaL}m^2_{\tilde{L}_iH_1}H^a_1 + \mathrm{h.c.}\ . \tag{5}$$

When lepton number is not conserved the sneutrinos may acquire vacuum expectation values (VEVs) $\langle\tilde{\nu}_{e,\mu,\tau}\rangle \equiv v_{e,\mu,\tau}/\sqrt{2}$. The SLHA1 defined the tree-level VEV v to be equal to $2m_Z/\sqrt{g^2+g'^2} \sim 246$ GeV; this is now generalised to

$$v = \sqrt{v_1^2 + v_2^2 + v_\mathrm{e}^2 + v_\mu^2 + v_\tau^2}\ . \tag{6}$$

For $\tan\beta$ we maintain the SLHA1 definition, $\tan\beta = v_2/v_1$.

The Lagrangian contains the (symmetric) neutrino/neutralino mass matrix as

$$\mathcal{L}^{\mathrm{mass}}_{\tilde{\chi}^0} = -\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 + \mathrm{h.c.}\ , \tag{7}$$

in the basis of 2–component spinors $\tilde{\psi}^0 = (\nu_e, \nu_\mu, \nu_\tau, -i\tilde{b}, -i\tilde{w}^3, \tilde{h}_1, \tilde{h}_2)^T$. We define the unitary 7×7 neutrino/neutralino mixing matrix N (block `RVNMIX`), such that:

$$-\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 = -\frac{1}{2}\underbrace{\tilde{\psi}^{0T}N^T}_{\tilde{\chi}^{0T}}\underbrace{N^*\mathcal{M}_{\tilde{\psi}^0}N^\dagger}_{\mathrm{diag}(m_{\tilde{\chi}^0})}\underbrace{N\tilde{\psi}^0}_{\tilde{\chi}^0}\ , \tag{8}$$

where the 7 (2–component) neutral leptons $\tilde{\chi}^0$ are defined strictly mass-ordered, i.e. with the 1^{st},2^{nd},3^{rd} lightest corresponding to the mass entries for the PDG codes `12`, `14`, and `16`, and the four heaviest to the PDG codes `1000022`, `1000023`, `1000025`, `1000035`.

Charginos and charged leptons may also mix in the case of L-violation. The Lagrangian contains

$$\mathcal{L}^{\mathrm{mass}}_{\tilde{\chi}^+} = -\frac{1}{2}\tilde{\psi}^{-T}\mathcal{M}_{\tilde{\psi}^+}\tilde{\psi}^+ + \mathrm{h.c.}\ , \tag{9}$$

in the basis of 2–component spinors $\tilde{\psi}^+ = (e^+, \mu^+, \tau^+, -i\tilde{w}^+, \tilde{h}^+_2)^T$, $\tilde{\psi}^- = (e^-, \mu^-, \tau^-, -i\tilde{w}^-, \tilde{h}^-_1)^T$ where $\tilde{w}^\pm = (\tilde{w}^1 \mp \tilde{w}^2)/\sqrt{2}$. We define the unitary 5×5 charged fermion mixing matrices U, V, blocks `RVUMIX, RVVMIX`, such that:

$$-\frac{1}{2}\tilde{\psi}^{-T}\mathcal{M}_{\tilde{\psi}^+}\tilde{\psi}^+ = -\frac{1}{2}\underbrace{\tilde{\psi}^{-T}U^T}_{\tilde{\chi}^{-T}}\underbrace{U^*\mathcal{M}_{\tilde{\psi}^+}V^\dagger}_{\mathrm{diag}(m_{\tilde{\chi}^+})}\underbrace{V\tilde{\psi}^+}_{\tilde{\chi}^+}\ , \tag{10}$$

where the generalised charged leptons $\tilde{\chi}^+$ are defined as strictly mass ordered, i.e. with the 3 lightest states corresponding to the PDG codes `11`, `13`, and `15`, and the two heaviest to the

codes `1000024`, `1000037`. For historical reasons, codes `11`, `13`, and `15` pertain to the negatively charged field while codes `1000024` and `1000037` pertain to the opposite charge. The components of $\tilde{\chi}^+$ in "PDG notation" would thus be `(-11,-13,-15,1000024,1000037)`. In the limit of CP conservation, U and V are chosen to be real.

R-parity violation via lepton number violation implies that the sneutrinos can mix with the Higgs bosons. In the limit of CP conservation the CP-even (-odd) Higgs bosons mix with real (imaginary) parts of the sneutrinos. We write the neutral scalars as $\phi^0 \equiv \sqrt{2}\mathrm{Re}\left\{(H_1^0, H_2^0, \tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)^T\right\}$, with the mass term

$$\mathcal{L} = -\frac{1}{2}\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 \ , \tag{11}$$

where $\mathcal{M}^2_{\phi^0}$ is a 5×5 symmetric mass matrix. We define the orthogonal 5×5 mixing matrix $\aleph$ (block `RVHMIX`) by

$$-\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 = -\underbrace{\phi^{0T}\aleph^T}_{\Phi^{0T}}\underbrace{\aleph\mathcal{M}^2_{\phi^0}\aleph^T}_{\mathrm{diag}(m^2_{\Phi^0})}\underbrace{\aleph\phi^0}_{\Phi^0} \ , \tag{12}$$

where Φ^0 are the neutral scalar mass eigenstates in strictly increasing mass order The states are numbered sequentially by the PDG codes `(25,35,1000012,1000014,1000016)`, regardless of flavour content.

We write the neutral pseudoscalars as $\bar{\phi}^0 \equiv \sqrt{2}\mathrm{Im}\left\{(H_1^0, H_2^0, \tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)^T\right\}$, with the mass term

$$\mathcal{L} = -\frac{1}{2}\bar{\phi}^{0T}\mathcal{M}^2_{\bar{\phi}^0}\bar{\phi}^0 \ , \tag{13}$$

where $\mathcal{M}^2_{\bar{\phi}^0}$ is a 5×5 symmetric mass matrix. We define the 4×5 mixing matrix $\bar{\aleph}$ (block `RVAMIX`) by

$$-\bar{\phi}^{0T}\mathcal{M}^2_{\bar{\phi}^0}\bar{\phi}^0 = -\underbrace{\bar{\phi}^{0T}\bar{\aleph}^T}_{\bar{\Phi}^{0T}}\underbrace{\bar{\aleph}\mathcal{M}^2_{\bar{\phi}^0}\bar{\aleph}^T}_{\mathrm{diag}(m^2_{\bar{\Phi}^0})}\underbrace{\bar{\aleph}\bar{\phi}^0}_{\bar{\Phi}^0} \ , \tag{14}$$

where $\bar{\Phi}^0$ are the pseudoscalar mass eigenstates in increasing mass order. The states are numbered sequentially by the PDG codes `(36,1000017, 1000018,1000019)`, regardless of flavour composition. The Goldstone boson G^0 has been explicitly left out and the 4 rows of $\bar{\aleph}$ form a set of orthonormal vectors.

If the blocks `RVHMIX, RVAMIX` are present, they supersede the SLHA1 `ALPHA` variable/block.

The charged sleptons and charged Higgs bosons also mix in the 8×8 mass squared matrix $\mathcal{M}^2_{\phi^\pm}$, which we diagonalise by a 7×8 matrix C (block `RVLMIX`):

$$\mathcal{L} = -\underbrace{(H_1^{-*}, H_2^+, \tilde{e}^*_{L_i}, \tilde{e}^*_{R_j})C^\dagger}_{\Phi^+}\underbrace{C\mathcal{M}^2_{\phi^\pm}C^\dagger}_{\mathrm{diag}(\mathcal{M}^2_{\Phi^\pm})}C\begin{pmatrix} H_1^- \\ H_2^{+*} \\ \tilde{e}_{L_k} \\ \tilde{e}_{R_l}\end{pmatrix} \ , \tag{15}$$

where $i,j,k,l \in \{1,2,3\}$, $\alpha,\beta \in \{1,\ldots,6\}$ and $\Phi^+ = \Phi^{-\dagger}$ are the charged scalar mass eigenstates arranged in increasing mass order. These states are numbered sequentially by

the PDG codes (37,1000011,1000013,1000015, 2000011,2000013,2000015), regardless of flavour composition. The Goldstone boson G^- has been explicitly left out and the 7 rows of C form a set of orthonormal vectors.

2.3 CP Violation

When CP symmetry is broken, quantum corrections cause mixing between the CP-even and CP-odd Higgs states. Writing the neutral scalar interaction eigenstates as $\phi^0 \equiv \sqrt{2}(\mathrm{Re}\{H_1^0\}, \mathrm{Re}\{H_2^0\}, \mathrm{Im}\{H_1^0\}, \mathrm{Im}\{H_2^0\})^T$ we define the 3×4 mixing matrix S (block CVHMIX) by

$$-\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 = -\underbrace{\phi^{0T}S^T}_{\Phi^{0T}}\underbrace{S^*\mathcal{M}^2_{\phi^0}S^\dagger}_{\mathrm{diag}(m^2_{\Phi^0})}\underbrace{S\phi^0}_{\Phi^0} \ , \tag{16}$$

where $\Phi^0 \equiv (h_1^0, h_2^0, h_3^0)^T$ are the mass eigenstates arranged in ascending mass order; these states are numbered sequentially by the PDG codes (25,35,36), regardless of flavour composition.

For the neutralino and chargino mixing matrices, the default convention in SLHA1 is that they be real matrices. One or more mass eigenvalues may then have an apparent negative sign, which can be removed by a phase transformation on $\tilde{\chi}_i$ as explained in SLHA1 [1]. When going to CPV, the reason for introducing the negative-mass convention in the first place, namely maintaining the mixing matrices strictly real, disappears. We therefore here take all masses real and positive, with N, U, and V complex. This does lead to a nominal dissimilarity with SLHA1 in the limit of vanishing CP violation, but we note that the explicit CPV switch in MODSEL can be used to decide unambiguously which convention to follow.

For the remaining MSSM parameters we use straightforward generalisations to the complex case, see section 3.4.

2.4 NMSSM

We shall here define the next-to-minimal case as having exactly the field content of the MSSM with the addition of one gauge-singlet chiral superfield. As to couplings and parameterisations, rather than adopting a particular choice, or treating each special case separately, below we choose instead to work at the most general level. Any particular special case can then be obtained by setting different combinations of couplings to zero. However, we do specialise to the SLHA1-like case without CP violation, R-parity violation, or flavour violation. Below, we shall use the acronym NMSSM for this class of models, but we emphasise that we understand it to relate to field content only, and not to the presence or absence of specific couplings.

We write the most general CP conserving NMSSM superpotential as (extending the notation of SLHA1):

$$W_{NMSSM} = W_{MSSM} - \epsilon_{ab}\lambda S H_1^a H_2^b + \frac{1}{3}\kappa S^3 + \mu' S^2 + \xi_F S \ , \tag{17}$$

where W_{MSSM} is the MSSM superpotential, in the conventions of ref. [1, eq. (3)]. A non-zero λ in combination with a VEV $\langle S \rangle$ of the singlet generates a contribution to the effective μ term $\mu_{\rm eff} = \lambda \langle S \rangle + \mu$, where the MSSM μ term is normally assumed to be zero, yielding $\mu_{\rm eff} = \lambda \langle S \rangle$. The remaining terms represent a general cubic superpotential for the singlet; κ is dimensionless, μ' has dimension of mass, and ξ_F has dimension of mass squared. The soft SUSY-breaking terms relevant to the NMSSM are

$$V_{\rm soft} = V_{2,MSSM} + V_{3,MSSM} + m_{\rm S}^2 |S|^2 + (-\epsilon_{ab} \lambda A_\lambda S H_1^a H_2^b + \frac{1}{3} \kappa A_\kappa S^3 + B' \mu' S^2 + \xi_S S + {\rm h.c.}) \ , \tag{18}$$

where $V_{i,MSSM}$ are the MSSM soft terms, in the conventions of ref. [1, eqs. (5) and (7)].

At tree level, there are thus 15 parameters (in addition to m_Z which fixes the sum of the squared Higgs VEVs) that are relevant for the Higgs sector:

$$\tan\beta, \ \mu, \ m_{H_1}^2, \ m_{H_2}^2, \ m_3^2, \ \lambda, \ \kappa, \ A_\lambda, \ A_\kappa, \ \mu', \ B', \ \xi_F, \ \xi_S, \ \lambda \langle S \rangle \, , \ m_S^2 \ . \tag{19}$$

The minimisation of the effective potential imposes 3 conditions on these parameters, such that only 12 of them can be considered independent. We leave it up to each spectrum calculator to decide on which combinations to accept. For the purpose of this accord, we note only that to specify a general model exactly 12 parameters from eq. (19) should be provided in the input, including explicit zeroes for parameters desired "switched off". However, since $\mu = m_3^2 = \mu' = B' = \xi_F = \xi_S = 0$ in the majority of phenomenological constructions, for convenience we also allow for a six-parameter specification in terms of the reduced parameter list:

$$\tan\beta, \ m_{H_1}^2, \ m_{H_2}^2, \ \lambda, \ \kappa, \ A_\lambda, \ A_\kappa, \ \lambda \langle S \rangle \, , \ m_S^2 \ . \tag{20}$$

To summarise, in addition to m_Z, the input to the accord should contain either 12 parameters from the list given in eq. (19), including zeroes for parameters not present in the desired model, or it should contain 6 parameters from the list in eq. (20), in which case the remaining 6 "non-standard" parameters, μ, m_3^2, μ', B', ξ_F, and ξ_F, will be assumed to be zero; in both cases the 3 unspecified parameters (as, e.g., $m_{H_1}^2$, $m_{H_2}^2$, and m_S^2) are assumed to be determined by the minimisation of the effective potential.

The CP-even neutral scalar interaction eigenstates are $\phi^0 \equiv \sqrt{2}{\rm Re}\left\{(H_1^0, H_2^0, S)^T\right\}$. We define the orthogonal 3×3 mixing matrix S (block `NMHMIX`) by

$$-\phi^{0T} \mathcal{M}^2_{\phi^0} \phi^0 = -\underbrace{\phi^{0T} S^T}_{\Phi^{0T}} \underbrace{S \mathcal{M}^2_{\phi^0} S^T}_{{\rm diag}(m^2_{\Phi^0})} \underbrace{S \phi^0}_{\Phi^0} \ , \tag{21}$$

where $\Phi^0 \equiv (h_1^0, h_2^0, h_3^0)$ are the mass eigenstates ordered in mass. These states are numbered sequentially by the PDG codes `(25,35,45)`. The format of `BLOCK NMHMIX` is the same as for the mixing matrices in SLHA1.

The CP-odd sector interaction eigenstates are $\bar{\phi}^0 \equiv \sqrt{2}{\rm Im}\left\{(H_1^0, H_2^0, S)^T\right\}$. We define the 2×3 mixing matrix P (block `NMAMIX`) by

$$-\bar{\phi}^{0T} \mathcal{M}^2_{\bar{\phi}^0} \bar{\phi}^0 = -\underbrace{\bar{\phi}^{0T} P^T}_{\bar{\Phi}^{0T}} \underbrace{P \mathcal{M}^2_{\bar{\phi}^0} P^T}_{{\rm diag}(m^2_{\bar{\Phi}^0})} \underbrace{P \bar{\phi}^0}_{\bar{\Phi}^0} \ , \tag{22}$$

where $\bar{\Phi}^0 \equiv (A_1^0, A_2^0)$ are the mass eigenstates ordered in mass. These states are numbered sequentially by the PDG codes `(36,46)`. The Goldstone boson G^0 has been explicitly left out and the 2 rows of P form a set of orthonormal vectors.

If `NMHMIX, NMAMIX` blocks are present, they supersede the SLHA1 `ALPHA` variable/block.

The Lagrangian contains the (symmetric) 5×5 neutralino mass matrix as

$$\mathcal{L}^{\rm mass}_{\tilde{\chi}^0} = -\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 + \text{h.c.}\ , \tag{23}$$

in the basis of 2–component spinors $\tilde{\psi}^0 = (-i\tilde{b},\ -i\tilde{w}^3,\ \tilde{h}_1,\ \tilde{h}_2,\ \tilde{s})^T$. We define the unitary 5×5 neutralino mixing matrix N (block `NMNMIX`), such that:

$$-\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 = -\frac{1}{2}\underbrace{\tilde{\psi}^{0T}N^T}_{\tilde{\chi}^{0T}}\underbrace{N^*\mathcal{M}_{\tilde{\psi}^0}N^\dagger}_{\text{diag}(m_{\tilde{\chi}^0})}\underbrace{N\tilde{\psi}^0}_{\tilde{\chi}^0}\ , \tag{24}$$

where the 5 (2–component) neutralinos $\tilde{\chi}_i$ are defined such that the absolute value of their masses increase with i. As in SLHA1, our convention is that N be a real matrix. One or more mass eigenvalues may then have an apparent negative sign, which can be removed by a phase transformation on $\tilde{\chi}_i$. The states are numbered sequentially by the PDG codes `(1000022,1000023,1000025,1000035,1000045)`.

3 Explicit Proposals for SLHA2

As in the SLHA1 [1], for all running parameters in the output of the spectrum file, we propose to use definitions in the modified dimensional reduction ($\overline{\rm DR}$) scheme.

To define the general properties of the model, we propose to introduce global switches in the SLHA1 model definition block `MODSEL`, as follows. Note that the switches defined here are in addition to the ones in [1].

3.1 Model Selection

`BLOCK MODSEL`

Switches and options for model selection. The entries in this block should consist of an index, identifying the particular switch in the listing below, followed by another integer or real number, specifying the option or value chosen:

`3` : (Default=`0`) Choice of particle content. Switches defined are:
- `0` : MSSM. This corresponds to SLHA1.
- `1` : NMSSM. As defined here.

`4` : (Default=`0`) R-parity violation. Switches defined are:
- `0` : R-parity conserved. This corresponds to the SLHA1.
- `1` : R-parity violated.

`5` : (Default=`0`) CP violation. Switches defined are:

- `0` : CP is conserved. No information even on the CKM phase is used. This corresponds to the SLHA1.
- `1` : CP is violated, but only by the standard CKM phase. All other phases assumed zero.
- `2` : CP is violated. Completely general CP phases allowed.

`6` : (Default=`0`) Flavour violation. Switches defined are:

- `0` : No (SUSY) flavour violation. This corresponds to the SLHA1.
- `1` : Quark flavour is violated.
- `2` : Lepton flavour is violated.
- `3` : Lepton and quark flavour is violated.

3.2 Flavour Violation

- All input SUSY parameters are given at the scale $M_{\rm input}$ as defined in the SLHA1 block `EXTPAR`, except for `EXTPAR 26`, which, if present, is the *pole* pseudoscalar Higgs mass. If no $M_{\rm input}$ is present, the GUT scale is used.

- For the SM input parameters, we take the Particle Data Group (PDG) definition: lepton masses are all on-shell. The light quark masses $m_{u,d,s}$ are given at 2 GeV in the $\overline{\rm MS}$ scheme, and the heavy quark masses are given as $m_c(m_c)^{\overline{\rm MS}}$, $m_b(m_b)^{\overline{\rm MS}}$ and $m_t^{\rm on-shell}$. The latter two quantities are already in the SLHA1. The others are added to `SMINPUTS` in the following manner:

  `8` : m_{ν_3}, pole mass.

  `11` : $m_{\rm e}$, pole mass.

  `12` : m_{ν_1}, pole mass.

  `13` : m_μ, pole mass.

  `14` : m_{ν_2}, pole mass.

  `21` : $m_d(2\ {\rm GeV})^{\overline{\rm MS}}$. d quark running mass in the $\overline{\rm MS}$ scheme.

  `22` : $m_u(2\ {\rm GeV})^{\overline{\rm MS}}$. u quark running mass in the $\overline{\rm MS}$ scheme.

  `23` : $m_s(2\ {\rm GeV})^{\overline{\rm MS}}$. s quark running mass in the $\overline{\rm MS}$ scheme.

  `24` : $m_c(m_c)^{\overline{\rm MS}}$. c quark running mass in the $\overline{\rm MS}$ scheme.

  The FORTRAN format is the same as that of `SMINPUTS` in SLHA1 [1].

- $V_{\rm CKM}$: the input CKM matrix, in the block `VCKMIN`, in terms of the Wolfenstein parameters:

1 : λ

2 : A

3 : $\bar{\rho}$

4 : $\bar{\eta}$

- $(\hat{m}^2_{\tilde{Q}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{u}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{d}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{L}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{e}})^{\overline{\rm DR}}_{ij}$: the squark and slepton soft SUSY-breaking masses at the input scale in the super-CKM/MNS basis, as defined above. They will be given in the new blocks `MSQ2IN`, `MSU2IN`, `MSD2IN`, `MSL2IN`, `MSE2IN`, with the same format as matrices in SLHA1. Only the "upper triangle" of these matrices should be given. If diagonal entries are present, these supersede the parameters in the SLHA1 block `EXTPAR`.

- $(\hat{T}_U)^{\overline{\rm DR}}_{ij}$, $(\hat{T}_D)^{\overline{\rm DR}}_{ij}$, and $(\hat{T}_E)^{\overline{\rm DR}}_{ij}$: the squark and slepton soft SUSY-breaking trilinear couplings at the input scale in the super-CKM/MNS basis. They will be given in the new blocks `TUIN`, `TDIN`, `TEIN`, in the same format as matrices in SLHA1. If diagonal entries are present these supersede the A parameters specified in the SLHA1 block `EXTPAR` [1].

For the output, the pole masses are given in block `MASS` as in SLHA1, and the $\overline{\rm DR}$ and mixing parameters as follows:

- $(\hat{m}^2_{\tilde{Q}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{u}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{d}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{L}})^{\overline{\rm DR}}_{ij}$, $(\hat{m}^2_{\tilde{e}})^{\overline{\rm DR}}_{ij}$: the squark and slepton soft SUSY-breaking masses at scale Q in the super-CKM/MNS basis. Will be given in the new blocks `MSQ2 Q=...`, `MSU2 Q=...`, `MSD2 Q=...`, `MSL2 Q=...`, `MSE2 Q=...`, with formats as the corresponding input blocks `MSX2IN` above.

- $(\hat{T}_U)^{\overline{\rm DR}}_{ij}$, $(\hat{T}_D)^{\overline{\rm DR}}_{ij}$, and $(\hat{T}_E)^{\overline{\rm DR}}_{ij}$: The squark and slepton soft SUSY-breaking trilinear couplings in the super-CKM/MNS basis. Given in the new blocks `TU Q=...`, `TD Q=...`, `TE Q=...`, which supersede the SLHA1 blocks `AD`, `AU`, and `AE`, see [1].

- $(\hat{Y}_U)^{\overline{\rm DR}}_{ii}$, $(\hat{Y}_D)^{\overline{\rm DR}}_{ii}$, $(\hat{Y}_E)^{\overline{\rm DR}}_{ii}$: the diagonal $\overline{\rm DR}$ Yukawas in the super-CKM/MNS basis, at the scale Q. Given in the SLHA1 blocks `YU Q=...`, `YD Q=...`, `YE Q=...`, see [1]. Note that although the SLHA1 blocks provide for off-diagonal elements, only the diagonal ones will be relevant here, due to the CKM rotation.

- The $\overline{\rm DR}$ CKM matrix at the scale Q. Will be given in the new block(s) `VCKM Q=...`, with entries defined as for the input block `VCKMIN` above.

- The new blocks R_u =`USQMIX` R_d =`DSQMIX`, R_e =`SELMIX`, and R_ν =`SNUMIX` specify the composition of the mass eigenstates in terms of the super-CKM/MNS basis states

according to the following definitions:

$$\begin{pmatrix} 1000001 \\ 1000003 \\ 1000005 \\ 2000001 \\ 2000003 \\ 2000005 \end{pmatrix} = \begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \\ \tilde{d}_4 \\ \tilde{d}_5 \\ \tilde{d}_6 \end{pmatrix}_{\text{mass}-\text{ordered}} = \texttt{DSQMIX}_{ij} \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \\ \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix}_{\text{super}-\text{CKM}} , \tag{25}$$

$$\begin{pmatrix} 1000002 \\ 1000004 \\ 1000006 \\ 2000002 \\ 2000004 \\ 2000006 \end{pmatrix} = \begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix}_{\text{mass}-\text{ordered}} = \texttt{USQMIX}_{ij} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}_{\text{super}-\text{CKM}} . \tag{26}$$

$$\begin{pmatrix} 1000011 \\ 1000013 \\ 1000015 \\ 2000011 \\ 2000013 \\ 2000015 \end{pmatrix} = \begin{pmatrix} \tilde{e}_1 \\ \tilde{e}_2 \\ \tilde{e}_3 \\ \tilde{e}_4 \\ \tilde{e}_5 \\ \tilde{e}_6 \end{pmatrix}_{\text{mass}-\text{ordered}} = \texttt{SELMIX}_{ij} \begin{pmatrix} \tilde{e}_L \\ \tilde{\mu}_L \\ \tilde{\tau}_L \\ \tilde{e}_R \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix}_{\text{super}-\text{MNS}} , \tag{27}$$

$$\begin{pmatrix} 1000012 \\ 1000014 \\ 1000016 \end{pmatrix} = \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{\nu}_2 \\ \tilde{\nu}_3 \end{pmatrix}_{\text{mass}-\text{ordered}} = \texttt{SNUMIX}_{ij} \begin{pmatrix} \tilde{\nu}_e \\ \tilde{\nu}_\mu \\ \tilde{\nu}_\tau \end{pmatrix}_{\text{super}-\text{MNS}} . \tag{28}$$

Note! A potential for inconsistency arises if the masses and mixings are not calculated in the same way, e.g. if radiatively corrected masses are used with tree-level mixing matrices. In this case, it is possible that the radiative corrections to the masses shift the mass ordering relative to the tree-level. This is especially relevant when near-degenerate masses occur in the spectrum and/or when the radiative corrections are large. In these cases, explicit care must be taken especially by the program writing the spectrum, but also by the one reading it, to properly arrange the rows in the order of the mass spectrum actually used.

3.3 R-Parity Violation

The input/output blocks for R-parity violating couplings are summarised in Tab. 1. The naming convention for input blocks is `BLOCK RV#IN`, where the '`#`' character represents the name of the relevant output block given below. Default inputs for all R-parity violating couplings are zero. The inputs are given at scale M_{input}, as described in SLHA1 (default is the GUT scale) and follow the output format given below (with the omission of `Q= ...`). In addition, the known fermion masses should be given in `SMINPUTS` as defined above.

For the output, the pole masses are given in block `MASS` as in SLHA1, and the $\overline{\text{DR}}$ and mixing parameters as follows:

Input block	Output block	data
RVLAMLLEIN	RVLAMLLE	$i\ j\ k\ \lambda_{ijk}$
RVLAMLQDIN	RVLAMLQD	$i\ j\ k\ \lambda'_{ijk}$
RVLAMUDDIN	RVLAMUDD	$i\ j\ k\ \lambda''_{ijk}$
RVTLLEIN	RVTLLE	$i\ j\ k\ T_{ijk}$
RVTLQDIN	RVTLQD	$i\ j\ k\ T'_{ijk}$
RVTUDDIN	RVTUDD	$i\ j\ k\ T''_{ijk}$
NB: One of the following RV...IN blocks must be left out: (which one up to user and RGE code)		
RVKAPPAIN	RVKAPPA	$i\ \kappa_i$
RVDIN	RVD	$i\ D_i$
RVSNVEVIN	RVSNVEV	$i\ v_i$
RVM2LH1IN	RVM2LH1	$i\ m^2_{\tilde{L}_i H_1}$

Table 1: Summary of R-parity violating SLHA2 data blocks. Only 3 out of the last 4 blocks are independent. Which block to leave out of the input is in principle up to the user, with the caveat that a given spectrum calculator may not accept all combinations.

- The dimensionless couplings λ_{ijk}, λ'_{ijk}, and λ''_{ijk} are given in `BLOCK RVLAMLLE, RVLAMLQD, RVLAMUDD Q= ...` respectively. The output standard should correspond to the FORTRAN format

  ```
  (1x,I2,1x,I2,1x,I2,3x,1P,E16.8,0P,3x,'#',1x,A) .
  ```

  where the first three integers in the format correspond to i, j, and k and the double precision number is the coupling.

- The soft SUSY-breaking couplings T_{ijk}, T'_{ijk}, and T''_{ijk} should be given in `BLOCK RVTLLE, RVTLQD, RVTUDD Q= ...`, in the same format as the λ couplings above.

- The bilinear superpotential and soft SUSY-breaking terms κ_i, D_i, and $m^2_{\tilde{L}_i H_1}$ and the sneutrino VEVs are given in `BLOCK RVKAPPA, RVD, RVM2LH1, RVSNVEV Q= ...` respectively, in the same format as real-valued vectors in the SLHA1.

- The new mixing matrices `RVNMIX`, `RVUMIX`, `RVVMIX`, `RVHMIX`, `RVAMIX`, and `RVLMIX` are described in section 2.2.

As for the R-conserving MSSM, the bilinear terms (both SUSY-breaking and SUSY-respecting ones, including μ) and the VEVs are not independent parameters. They become related by the condition of electroweak symmetry breaking. This carries over to the RPV case, where not all the parameters in the input blocks `RV...IN` in Tab. 1 can be given simultaneously. Specifically, of the last 4 blocks only 3 are independent. One block is determined by minimising the Higgs-sneutrino potential. We do not here insist on a particular choice for which of `RVKAPPAIN`, `RVDIN`, `RVSNVEVIN`, and `RVM2LH1IN` to leave out, but leave it up to the spectrum calculators to accept one or more combinations.

3.4 CP Violation

When adding CP violation to the MSSM model parameters and mixing matrices, the SLHA1 blocks are understood to contain the real parts of the relevant parameters. The imaginary parts should be provided with exactly the same format, in a separate block of the same name but prefaced by `IM`. The defaults for all imaginary parameters will be zero.

One special case is the μ parameter. When the real part of μ is given in `EXTPAR 23`, the imaginary part should be given in `IMEXTPAR 23`, as above. However, when $|\mu|$ is determined by the conditions for electroweak symmetry breaking, only the phase φ_μ is taken as an input parameter. In this case, SLHA2 generalises the entry `MINPAR 4` to contain the cosine of the phase (as opposed to just sign(μ) in SLHA1), and we further introduce a new block `IMMINPAR` whose entry `4` gives the sine of the phase, that is:

`BLOCK MINPAR`

`4` : CP conserved: sign(μ).
CP violated: $\cos\varphi_\mu = \mathrm{Re}\{\mu\}/|\mu|$.

`BLOCK IMMINPAR`

`4` : CP conserved: n/a.
CP violated: $\sin\varphi_\mu = \mathrm{Im}\{\mu\}/|\mu|$.

Note that $\cos\varphi_\mu$ coincides with sign(μ) in the CP-conserving cases.

The new 3×4 block S =`CVHMIX` specifies the composition of the mass eigenstates in terms of the interaction basis states according to the following definition:

$$\begin{pmatrix} 25 \\ 35 \\ 36 \end{pmatrix} = \begin{pmatrix} h_1^0 \\ h_2^0 \\ h_3^0 \end{pmatrix}_{\mathrm{mass-ordered}} = \mathtt{CVHMIX}_{ij} \begin{pmatrix} \sqrt{2}\mathrm{Re}\{H_1^0\} \\ \sqrt{2}\mathrm{Re}\{H_2^0\} \\ \sqrt{2}\mathrm{Im}\{H_1^0\} \\ \sqrt{2}\mathrm{Im}\{H_2^0\} \end{pmatrix} . \tag{29}$$

In order to translate between S and other conventions, the tree-level angle α may be needed. This should be given in the SLHA1 output `BLOCK ALPHA`:

`BLOCK ALPHA`

CP conserved: α; precise definition up to spectrum calculator, see SLHA1.
CP violated: α_{tree}. Must be accompanied by the matrix S, as described above, in the block `CVHMIX`.

3.5 NMSSM

Firstly, as described above, `BLOCK MODSEL` should contain the switch 3 with value 1, corresponding to the choice of the NMSSM particle content.

Secondly, for the parameters that are also present in the MSSM, we re-use the corresponding SLHA1 entries. That is, m_Z should be given in `SMINPUTS` entry `4` and $m^2_{H_1}, m^2_{H_2}$ can be given in the `EXTPAR` entries `21` and `22`. $\tan\beta$ should either be given in `MINPAR` entry 3 (default) or `EXTPAR` entry 25 (user-defined input scale), as in SLHA1. If μ should be desired non-zero, it can be given in `EXTPAR` entry `23`. The corresponding soft parameter m_3^2 can be given in `EXTPAR` entry `24`, in the form $m_3^2/(\cos\beta \sin\beta)$, see [1].

Further, new entries in `BLOCK EXTPAR` have been defined for the NMSSM specific input parameters, as follows. As in the SLHA1, these parameters are all given at the common scale $M_{\rm input}$, which can either be left up to the spectrum calculator or given explicitly using `EXTPAR 0` (see [1]):

`BLOCK EXTPAR`

Input parameters specific to the NMSSM (i.e., in addition to the entries defined in [1])

- `61` : λ. Superpotential trilinear Higgs SH_2H_1 coupling.
- `62` : κ. Superpotential cubic S coupling.
- `63` : A_λ. Soft trilinear Higgs SH_2H_1 coupling.
- `64` : A_κ. Soft cubic S coupling.
- `65` : $\lambda\langle S\rangle$. Vacuum expectation value of the singlet (scaled by λ).
- `66` : ξ_F. Superpotential linear S coupling.
- `67` : ξ_S. Soft linear S coupling.
- `68` : μ'. Superpotential quadratic S coupling.
- `69` : B'. Soft quadratic S coupling.
- `70` : m_S^2. Soft singlet mass squared.

Important note: only 12 of the parameters listed in eq. (19) should be given as input at any one time (including explicit zeroes for parameters desired "switched off"), the remaining ones being determined by the minimisation of the effective potential. Which combinations to accept is left up to the individual spectrum calculator programs. Alternatively, for minimal models, 6 parameters of those listed in eq. (20) should be given.

In the spectrum output, running NMSSM parameters corresponding to the `EXTPAR` entries above can be given in the block `NMSSMRUN Q=...`:

`BLOCK NMSSMRUN Q=...`

Output parameters specific to the NMSSM, given in the $\overline{\rm DR}$ scheme, at the scale Q. As in the SLHA1, several of these blocks may be given simultaneously in the output, each then

corresponding to a specific scale, but at least one should always be present. See corresponding entries in `EXTPAR` above for definitions.

`1` : $\lambda(Q)^{\overline{\rm DR}}$.

`2` : $\kappa(Q)^{\overline{\rm DR}}$.

`3` : $A_\lambda(Q)^{\overline{\rm DR}}$.

`4` : $A_\kappa(Q)^{\overline{\rm DR}}$.

`5` : $\lambda \langle S \rangle (Q)^{\overline{\rm DR}}$.

`6` : $\xi_F(Q)^{\overline{\rm DR}}$.

`7` : $\xi_S(Q)^{\overline{\rm DR}}$.

`8` : $\mu'(Q)^{\overline{\rm DR}}$.

`9` : $B'(Q)^{\overline{\rm DR}}$.

`10` : $m_S^2(Q)^{\overline{\rm DR}}$.

The new 3×3 block $S =$`NMHMIX` specifies the composition of the mass eigenstates in terms of the interaction basis states according to the following definition:

$$\begin{pmatrix} 25 \\ 35 \\ 45 \end{pmatrix} = \begin{pmatrix} h_1^0 \\ h_2^0 \\ h_3^0 \end{pmatrix}_{\rm mass-ordered} = \texttt{NMHMIX}_{ij} \begin{pmatrix} \sqrt{2}{\rm Re}\left\{H_1^0\right\} \\ \sqrt{2}{\rm Re}\left\{H_2^0\right\} \\ \sqrt{2}{\rm Re}\left\{S\right\} \end{pmatrix} . \tag{30}$$

The new 2×3 block $S =$`NMAMIX` specifies the composition of the mass eigenstates in terms of the interaction basis states according to the following definition:

$$\begin{pmatrix} 36 \\ 46 \end{pmatrix} = \begin{pmatrix} A_1^0 \\ A_2^0 \end{pmatrix}_{\rm mass-ordered} = \texttt{NMAMIX}_{ij} \begin{pmatrix} \sqrt{2}{\rm Im}\left\{H_1^0\right\} \\ \sqrt{2}{\rm Im}\left\{H_2^0\right\} \\ \sqrt{2}{\rm Im}\left\{S\right\} \end{pmatrix} . \tag{31}$$

Finally, the new 5×5 block `NMNMIX` gives the neutralino mixing matrix, with the fifth mass eigenstate labelled `1000045` and the fifth interaction eigenstate being the singlino, $\tilde{s}$.

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